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Numerical investigation of Linear Particle Chain impact dampers with friction

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ABSTRACT

Impact dampers were first introduced in 1934 and the research and development on improving their performance and configuration is still ongoing to date. In this paper, the recently developed Linear Particle Chain (LPC) impact damper is experimentally and numerically studied. The damper was attached to a single-degree-of-freedom structure represented by a spring damper system and released from an initial position. A SOLIDWORKS model for the damper has been developed and numerically simulated using the finite element approach. The Coulomb friction model of the colliding masses is added to the overall structure. The response of the system was analyzed and compared to the experimental results. The simulation model showed a faster decay when the number of balls in the LPC impact damper was increased and when different mass ratios were used which is in agreement with the experimental results.

1. Introduction

One important field of research, over the last few decades, has been very much centered at mitigating the harms of natural disasters such as earthquakes and severe storms. The reason for the focus is the possible immense impact of vibration induced failures on lives and businesses. For example, over 250,000 people died due to the 2010 Haiti 7.0 magnitude earthquake. Poor design and construction of structures has been identified as the main reason for the failures resulting from earthquakes and severe storms. In order to mitigate damages to standing structures, various designs for vibration dampers can be found in the literature and can be categorized into active and passive dampers [1]. Design of passive dampers has been an area of interest to vibration engineers as these dampers do not require energy input to successfully dampen out vibrations. One of the most commonly known mass dampers is the impact damper, also known as the acceleration damper. This device was first introduced in 1934 [2], and to date, research and development is still being carried out to improve its performance and devise new configurations [3]. A brief literature review of previous work on acceleration dampers can be found in [4].

The main objective of this work is to numerically and experimentally validate the dynamic behavior of a newly developed Linear Particle Chain (LPC) impact damper. First, an experimental test-bed was constructed which consists of a single-degree-of-freedom (SDOF) flexible structure, the LPC damper, and several distance measuring sensors. For the numerical modeling of the damper, the commercially available software SOLIDWORKS (SW) was used for the synthesis as well as the

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analysis of the LPC damper system [5]. First, the geometrical and physical parameters of the structure and the damper were directly measured or experimentally identified and used to construct the model of the damper system in SW. Then, the SW model is analyzed and the results are compared to those obtained from the experimental test-bed. It is worth noting that the friction between the damper mass and the primary system was accounted for using the Coulomb friction model.

In Section 2, a summary of the CAD modeling process, the different parts modeled using SW, and the experimental setup are described. In Section 3, the boundary conditions and variables are determined and the numerical solution obtained from SW is compared against the experimental results to show the agreement between the actual system and the virtual one. A brief discussion and remarks on major findings are presented in Section 4. Finally, conclusions are made in Section 5.

2. The impact damper model

2.1. The numerical technique

There are several techniques that can be used to model the dynamic behavior of structural systems such as the LPC damper. These include Lagrange, Hamiltonian, Newtonian, and the finite element techniques. Despite the simplicity of the LPC damper, developing an accurate model describing its motion concisely is tedious and challenging. Fortunately, there are several commercial CAD packages which can be used to model dynamic systems effortlessly. SOLIDWORKS is one of them and it is widely used in engineering schools. The software provides tools to synthesize the system in 3D and analyze it using finite element methods [5]. The SW solver offers three numerical stiff integration methods: Gear (GSTIFF), Modified Gear (WSTIFF), and Stabilized Index-2 (SI2_GSTIFF) methods [6,7]. The three solvers use Newton–Raphson iterations to solve coupled differential equations while satisfying algebraic constraint equations at every time step. The differences between these solvers are in the order (variable/constant), step size (variable/constant), and error control. For more details about the analysis process and solution options, the reader can refer to [8,9]. In this work, the three solvers are used depending on the case to be solved. The impact damper and SDOF structure are modeled and numerically analyzed as follows:

1) Creating the mathematical model; Preprocessor phase: This phase consists of creating the CAD model and adding/defining material properties of each part.
2) Creating the finite element model; Solution phase: Physical constraints and loading are specified and the type of analysis to be used is selected (i.e., static or dynamic).
3) Analyzing the system behavior; Postprocessing: The LPC damper system with the structure is analyzed and solutions for each moving part of the system are generated in terms of displacement and stress.

SOLIDWORKS package has a standard library of material mechanical and dynamic properties. In this work, the selected friction and impact law models are the Coulomb friction and kinematic impact law models, respectively. The coefficient of friction (COF) and coefficient of restitution (COR) between contact surfaces in contact are identified experimentally.

2.2. The experimental setup

The LPC impact damper consists of a linear arrangement of freely moving large (L) and small (S) balls constrained by two rigid stops. This design is considered as an extension of the single-container multi-unit impact damper but with different mass ratio of colliding masses. An additional parameter, compared to the conventional impact dampers, characterizing the

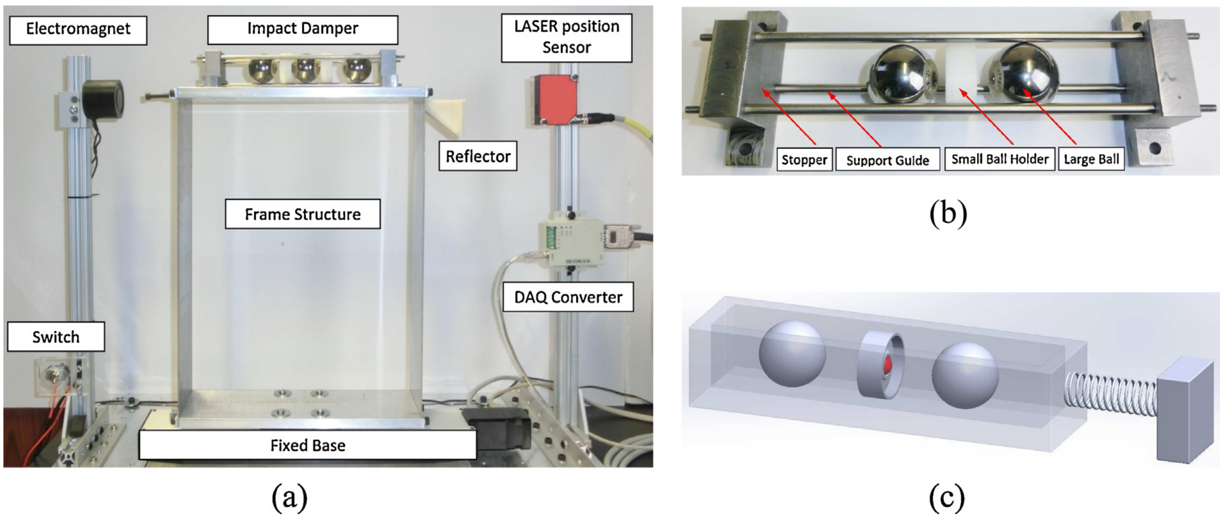

Fig. 1. The experiment and model components: (a) experiment setup; (b) LPC impact damper prototype; and (c) LPC impact damper SOLIDWORKS model.

LPC impact damper is the balls mass ratio (MR_B), which is defined as the mass ratio between the large and small balls. The mass ratio between the damper balls and the structure (MR_S) is not investigated in this work; however, several studies have investigated the effect of MR_S on the performance of impact dampers and concluded that higher mass ratios result in enhanced response attenuation [10,11].

In this work, the numerical simulation results obtained from SW are compared to the free vibration experiment. The experiment setup is shown in Fig. 1a, the damper prototype is shown Fig. 1b, and the SOLIDWORKS model of the damper used in the numerical simulation is shown in Fig. 1c.

The damper prototype consists of three guide rods for the balls, two rigid stops, n large balls, and $(n-1)$ small balls (where $n = 2, 3, \ldots$). For example, a 2L1S LPC impact damper consists of two large and one small balls. The material of the balls, guide rods, and stoppers are Chrome Steel, Stainless Steel, and Mild Steel, respectively. The small ball was aligned between the larger balls using a 3D printed circular disk made from ABS material. The disk is made such that the small ball is allowed to impact with the bounding larger balls at the common center line. Table 1 lists the numerical values characterizing all the parts used in the experimental work and adopted in the SW model. The guide rods and stoppers are modeled in SOLIDWORKS as a rectangular container with an open top to guarantee contact between the balls and the rails at all times. It is worth noting that when the guide rails were modeled as slender rods, simultaneous contact between all three rods and the balls did not occasionally occur due to unavoidable computational errors. Hence, the decision was made to replace the three rods with an open rectangular container to guarantee three contact points with every ball at all times. The mass of the container is set in SOLIDWORKS to the sum of the empty damper and the floor mass in the prototype. The SDOF flexible structure was modeled as mass-spring-damper system with the same characteristics (stiffness and damping coefficients) as the main structure (see Fig. 1c). The stiffness, damping coefficients, and friction coefficients are identified from the direct

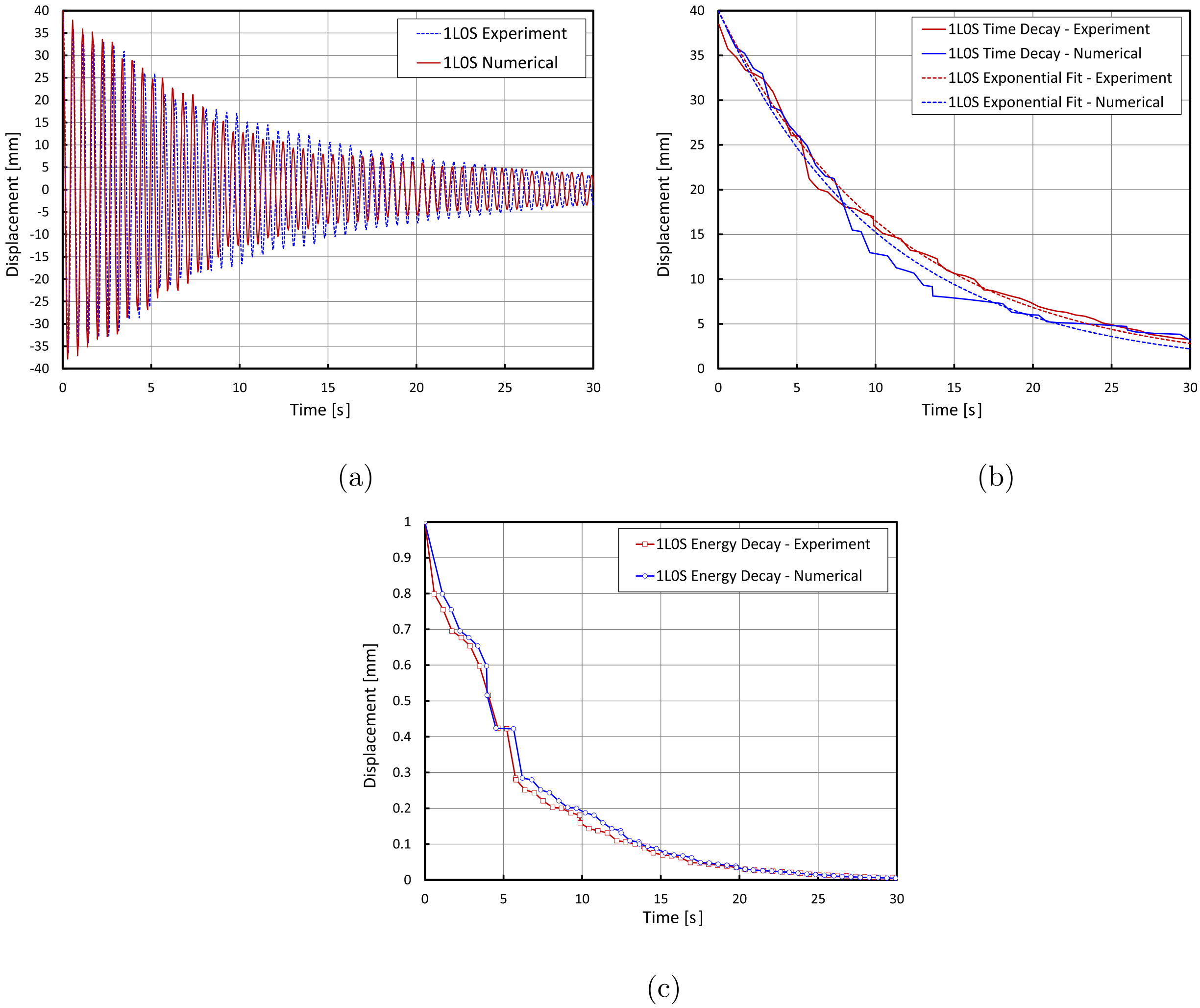

Fig. 2. Numerical and experimental response for single unit (1L0S) impact damper: (a) displacement time response; (b) displacement decay rate; and (c) energy decay rate.

Table 1
Numerical values used in the simulations.

Quantity	Value	Units	Quantity	Value	Units
Structure and empty damper mass	2.556	kg	COR (ball-wall)	0.81	–
Structure stiffness coefficient	313.01	N/m	COR (ball-ball)	0.93	–
Structure damping coefficient	0.157	N s/m	COF (ball-wall)	0.003	–
Large ball mass	0.2268	kg	COF (ball-ball)	0.0002	–
Small ball and holder mass	0.0128	kg	COF (holder-wall)	0.03	–
Large ball diameter	0.0381	m	Damper length	0.2	m
Small ball diameter	0.0127	m	Initial position	0.04	m

comparisons between the frame structure experimental response and the mass spring model simulations. The same initial conditions are imposed for the experiment and the numerical simulations. Free vibration experiments were conducted by releasing the top floor of the structure from an initial position and the resulting displacement was measured using LASER sensors. Videos of the experimental data presented in this paper are uploaded as supplementary files with this paper.

3. Simulation results

The main objective of this work is to investigate the accuracy of a numerical model developed using a commercially available software (SOLIDWORKS) to model the dynamic behavior of the LPC impact damper. Figs. 2a–5a show the displacement time response for the SDOF structure with single unit (1L0S), multi-unit (2L0S and 3L0S), and LPC (2L1S) impact dampers, respectively. The figures show that the attenuation of the displacement response decreases as the number

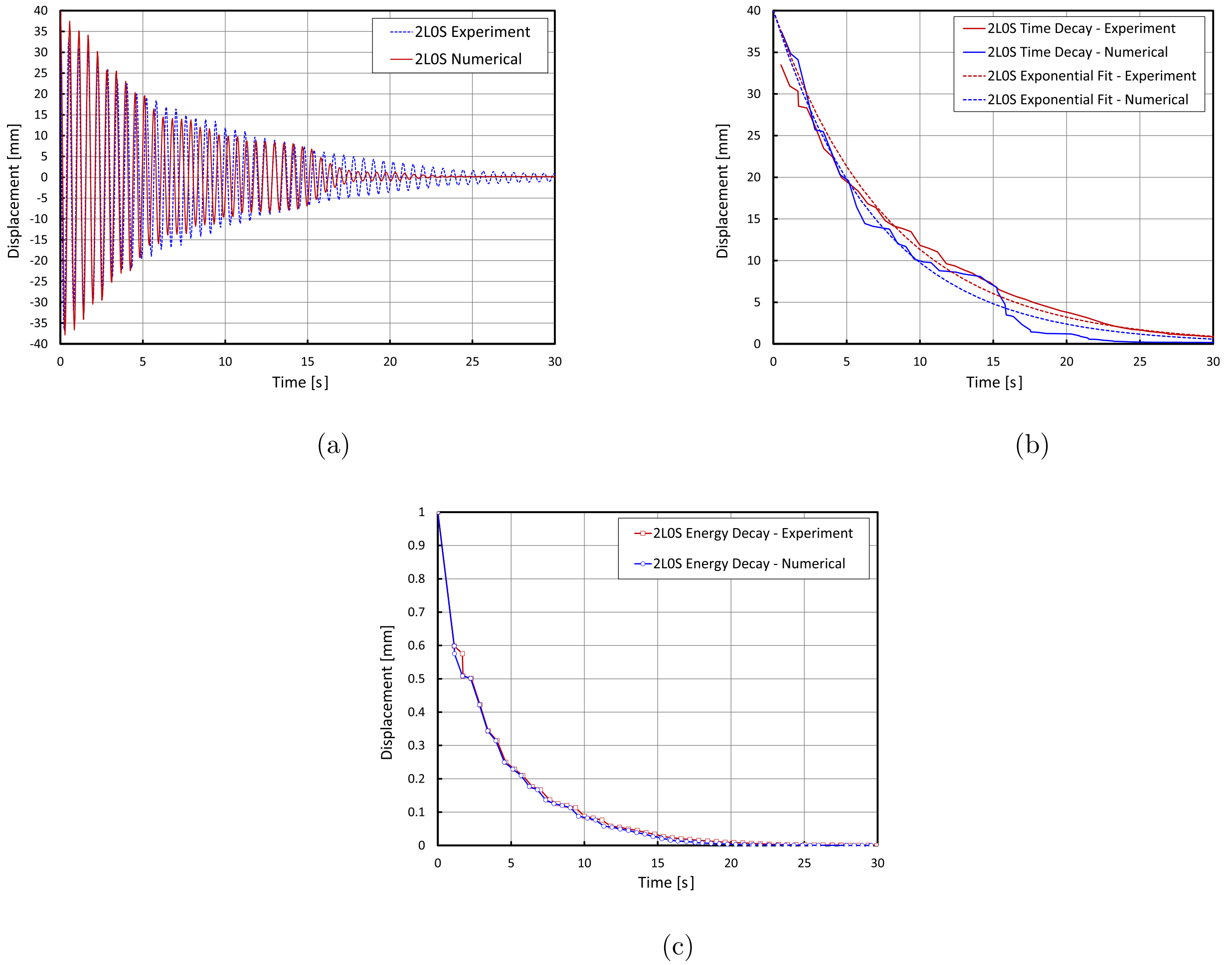

Fig. 3. Numerical and experimental response for multi-unit (2L0S) impact damper: (a) displacement time response; (b) displacement decay rate; and (c) energy decay rate.

of masses increases. It is clear from the SW simulation results that the insertion of the small ball between two larger balls leads to significant dampening of the primary system; this is also supported by the experimental results.

Figs. 2b–5b show two groups of curves: (i) the exact decay envelopes of the time responses; (ii) the fitted exponential curves for the time decay; and the exponential fitted curves are obtained by fitting the experimental and numerical time response decay envelopes to the function $A_o \exp(-\zeta\omega_n t)$, where $A_o = 40$ mm is the initial displacement, ζ is the damping ratio, and $\omega_n = 1.726$ Hz is the natural frequency of the primary system [12]. Table 2 summarizes the computed experimental and numerical values of the damping ratios. Figs. 2c–5c show the energy decay curves of the primary system. The energy decay curves are obtained by computing the ratio of the energy lost within each cycle (E_i) to the inial energy of the primary system (E_o) [13]. At the peak displacement, the velocity is zero, and therefore the energy ratio in the system is defined as:

$$\frac{E_i}{E_o} = \frac{(1/2)kx_i^2}{(1/2)kx_o^2} = \frac{x_i^2}{x_o^2} \tag{1}$$

where x_o, x_i, and k are the primary structure initial displacement, peak displacement, and stiffness, respectively.

4. Discussion and remarks

The highly nonlinear nature of the LPC damper system makes it initial condition dependent. The nonlinearities originate from the contact between the rails and the balls and between the balls themselves. Therefore, the initial position of the balls before the system is released from its initial position (the spring is compressed by 40 mm) heavily impacts the output response of the system which has been proven numerically and experimentally. It was clear from the numerical and experimental results that the overall attenuation in the deflection is small when the number of balls in the LPC is reduced

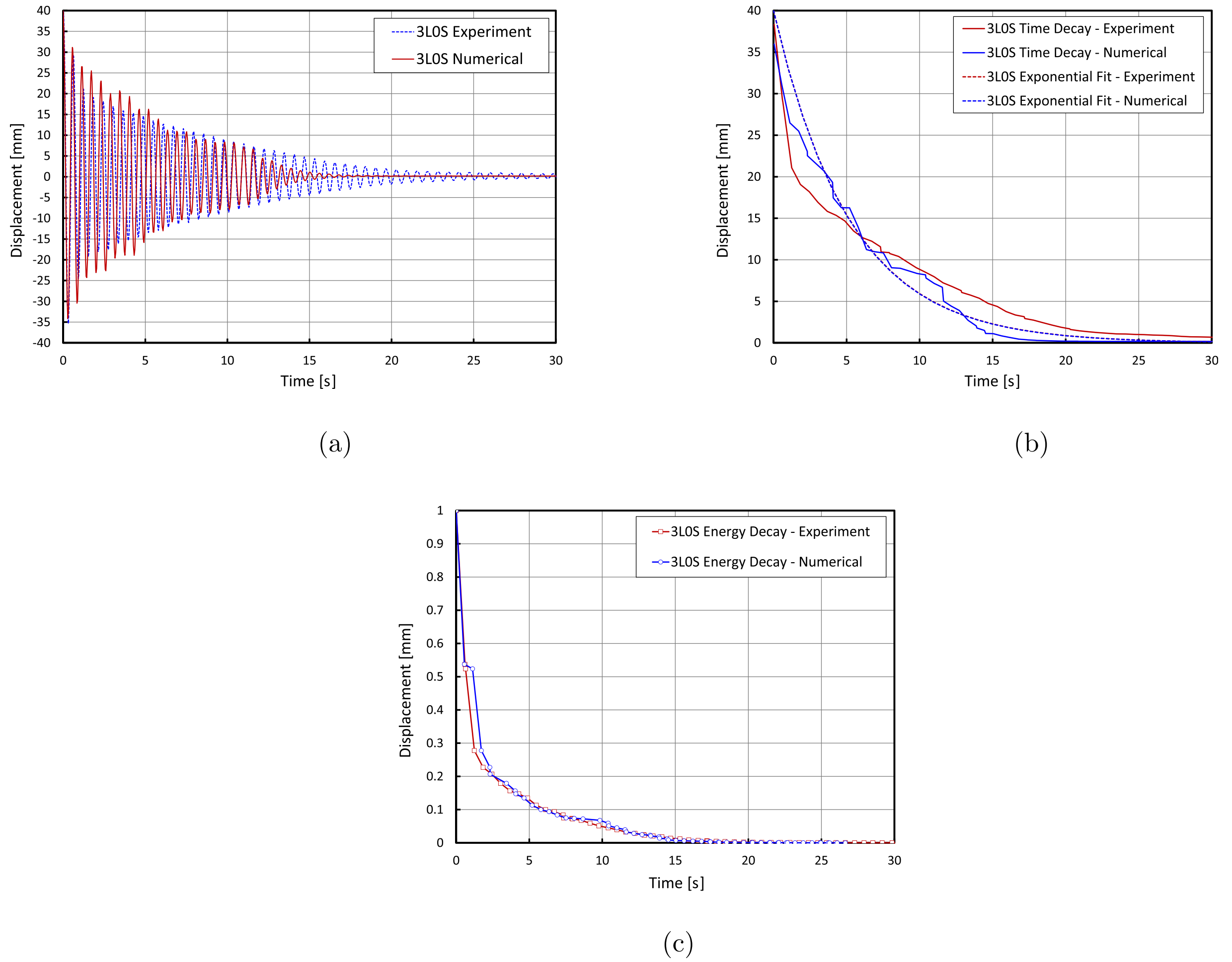

Fig. 4. Numerical and experimental response for multi-unit (3LOS) impact damper: (a) displacement time response; (b) displacement decay rate; and (c) energy decay rate.

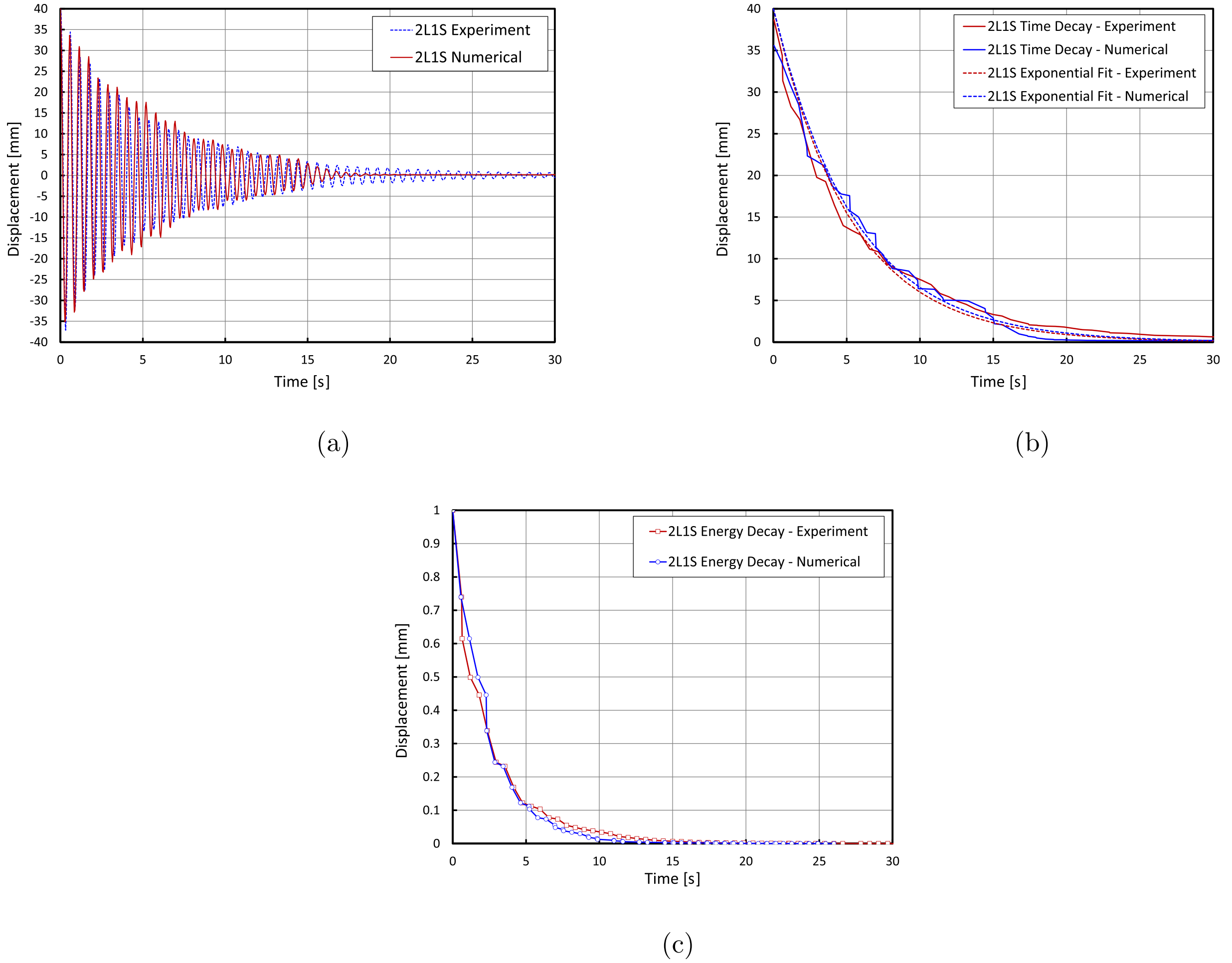

Fig. 5. Numerical and experimental response for LPC (2L1S) impact damper: (a) displacement time response; (b) displacement decay rate; and (c) energy decay rate.

Table 2
Numerical and experimental damping ratios.

Arrangement	Experimental	Numerical	% difference
0L0S	0.0175	0.0171	2.58
1L0S	0.0502	0.0548	−9.23
2L0S	0.0716	0.0801	−11.89
3L0S	0.1084	0.1088	0.41
2L1S	0.1079	0.1027	4.85

(see Figs. 2–5). This is due to the reduction in the distance that each ball has to travel before each collision. Therefore, the collisions will not be as efficient as needed in dissipating the unwanted energy.

Another design modification was investigated in this study which is the use of different size balls in the damper. The SW simulation results showed that the use of smaller balls of lighter weight between larger spheres increases the damping effect. This was also validated through our experiment which showed that the small ball collides several times between the larger ones and hence increasing the total energy dissipation. In fact, the number of observed and predicted collisions are very close, but different (more collisions predicted (12 impacts) than observed (10 impacts) in the first 20 s) and this could be due to the friction model adopted by SW. The out of phase collision are identified by visual observation from the recorded experiment videos in the high speed mode and SW animation. Although friction is usually treated as a source of energy dissipation, it is not true in the case of the LPC damper system. When the friction in the SW model was set to zero, it was observed that the damping effect significantly increased due to the increased number of out of phase collisions between the balls. The number of out of phase collisions increased from 6 when friction is included in the model to 22 in the case of no friction during the first 10 s. Moreover, some ball and stopper collisions could be in phase resulting in a temporary increase in the amplitude of vibration of the system.

Another key factor in increasing the damping effect of the LPC is the coefficient of restitution (COR) of the colliding bodies. It was noticed that when the COR of the contact surfaces in collision (ball and stopper) was increased, the number of out of phase hits increased and hence the total energy dissipation was higher.

In addition, the mass of the colliding bodies must be chosen carefully in order to achieve significant damping results. The damper to structure mass ratio plays a significant role in the system response. It was noticed, numerically and experimentally, that using heavier balls had a larger attenuation effect on the system response than when lighter ones were used. This can be attributed to the energy required to change the momentum of the heavier balls; hence, there is a larger momentum exchange between the balls and the stoppers. For more details about the effect of damper to structure mass ratio, the reader can refer to [10,11].

Finally, it is worth noting that numerical simulation in SW is sensitive to the selected solver, the desired solution accuracy, and the numerical integration parameters. However, once the physical parameters are identified, tuning the simulation parameters becomes effortless and the virtual model can be used to reduce costly experiments efficiently.

5. Conclusion

In this work, the time response of a Linear Particle Chain (LPC) impact damper coupled with a single-degree-of-freedom (SDOF) system is investigated numerically and validated experimentally. The commercially available software SOLIDWORKS (SW) was used for the numerical modeling as well as the analysis of the LPC damper system. The numerical model predicts the dynamic response of the actual system accurately and can be used to optimize the damper characteristics for highest energy dissipation and for specific application without resorting to expensive testing equipment. The numerical and experimental results led to the following conclusions:

i Increasing the number of balls and reducing the free spacing between them may be counterproductive in terms of overall mass of the damper and damping performance.
ii Reducing friction between the glides and the ball and/or increasing the coefficient of restitution, increases the number of out of phase hits leading to improved damper performance.
iii Increasing the mass of the balls leads to larger momentum exchange with the structure; hence, a higher damping effect is achieved.

Supplemental data

The videos show sample experiments with 1L0S, 2L0S, 3L0S, and 2L1S impact dampers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.csmssp.2016.03.001.

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